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Closed Cycle Magnetohydrodynamic Nuclear Space Power Generation Using Helium/Xenon Working Plasma

R.J. Litchford
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

N. Harada
Nagaoka University of Technology, Nagaoka, Japan

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R.J. Litchford
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Nagaoka University of Technology, Nagaoka, Japan

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

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ACRONYMS AND SYMBOLS

AR	advanced radioisotopes
CCMHD	closed cycle magnetohydrodynamic
He	helium
IFC	internal confinement fission
MHD	magnetohydrodynamic
MIG	mixed inert gas
MSFC	Marshall Space Flight Center
NFR	nuclear fission reactor
RF	radio frequency
SCM	superconducting magnet
T.I.T.	Tokyo Institute of Technology
Xe	xenon

NOMENCLATURE

A	cross-sectional area
J_{rad}	current density
M	Mach number
p	pressure
p_s	static pressure
Q	thermal power
Q_{GC}	gas cooler power
Q_{IC}	intercooler power
Q_{MHD}	thermal power at MHD generator inlet
Q_{rad}	radiation power
Q_{reg}	regenerator power
R_{eff}	regenerator efficiency
s	entropy
T	temperature
u	velocity
u_r	radial velocity
V_H	Hall potential
α	specific mass
σ	electrical conductivity

TECHNICAL PUBLICATION

CLOSED CYCLE MAGNETOHYDRODYNAMIC NUCLEAR SPACE POWER GENERATION USING HELIUM/XENON WORKING PLASMA

1. INTRODUCTION

Power generation systems in deep space, relatively far from the Sun, cannot rely on solar energy because the available energy is inversely proportional to the square of the distance from the Sun. Missions to Jupiter, Jupiter's icy moons, and beyond will require an alternative heat source and an efficient electric power generation system. Even for relatively large powered mission (>0.1 MWe) to Mars, it has been reported that utilization of solar panels costs much more than utilization of nuclear electric power.[1]

In the first step of the Jupiter Icy Moons Orbiter (JIMO) project, electric propulsion systems with output capabilities of 100–110 kWe are being considered and developed. Also, in the Prometheus project, nuclear electric power generation systems using advanced radioisotopes (ARs) or nuclear fission reactors (NFRs) are under investigation. For missions requiring greater electric power, NFR and efficient electric power generator systems must be used. Here, a closed cycle magnetohydrodynamic (CCMHD) power conversion system without bottoming cycle is proposed owing to its high efficiency and compactness.

Thus far, thermoelectric converters, stirling engines, and turbo-Brayton cycles have been considered and studied as power conversion systems in combination with AR power for relatively smaller missions and with NFR for larger missions.[2–6] In particular, for large missions requiring over 1 MWe, an electric power gas-cooled NFR with a CCMHD system has also been considered and studied.[7,8] In general, a helium (He) and xenon (Xe) mixture is used as a coolant in the gas-cooled reactor due to that mixture's excellent heat transfer performance when flowing and good thermal insulation performance when stagnant.[9] The utilization of mixed inert gas (MIG), He and Xe in this case, has also been proposed as a working medium for the CCMHD generator to avoid using a condensable alkali-metal seed.[10,11] Therefore, the proposed CCMHD system can be directly driven by a gas-cooled NFR and has the potential to achieve a lower specific mass. A comparison of plant efficiency has been performed, and the CCMHD single cycle was shown to have the highest plant efficiency—up to 60 percent—when combined with an inertial confinement fusion (ICF) reactor.[12] Such high efficiency is mainly due to the elimination of waste heat from a condenser and the reduction of gas cooler waste. However, a stand alone magnetohydrodynamic (MHD) power conversion system is more suitable for spacecraft applications. From the view point of system analysis, the type of heat source is not important and the same results are expected if output temperature and pressure are similar.

Electric power supply systems for space applications not only require high efficiency and high reliability, but low specific mass, as well. For thermoelectric converters, a low efficiency of around 6 to 7 percent increases specific mass up to ≈200 kg/kWe.[5] For turbo-Brayton systems, specific mass is ≈30 kg/kWe with a conversion efficiency of 20–40 percent for a lower electric output system.[5] It is hard to reduce the specific mass of a turbo-Brayton system below 10 kg/kWe, even for relatively greater output power systems. For future multimegawatt scale power supply systems, the direct drive NFR/CCMHD system is the most hopeful candidate. In this Technical Publication, an NFR/CCMHD system is described, system analyses are presented, and the specific mass characteristics of the system are estimated.

2. NUCLEAR FISSION REACTOR/CLOSED CYCLE MAGNETOHYDRO-DYNAMIC SPACE POWER PLANT

Previous systems analysis for CCMHD power conversion using an IFC reactor showed the highest efficiency among steam turbine, gas turbine, CCMHD, and their possible combined cycles.[12] Therefore, an NFR driven CCMHD space power plant has been adopted for detailed consideration. Figure 1 shows a schematic of the complete NFR/CCMHD power generation system.

A working medium of He mixed with Xe is used to connect the CCMHD system directly to the NFR. Alkali-metal seed is excluded from the system to avoid condensed phase handling issues, and a MIG system is adapted a s a means of eliminating the system complexity associated with seed injection, mixing, and recovery.[10,11] However, the ionization potential of a MIG working medium is much higher than that of alkali-metal; therefore, the ionization level, namely electrical conductivity, is too low at the reactor exit temperature (≈1,800 K) and nonthermal pre-ionization is required. Thus far, microwave, electron beam, helicon, and RF systems have been considered, and the most suitable one—in terms of effectiveness, reliability, economy and specific mass attributes—is yet to be determined.

A disk-shaped Hall-type MHD generator is used because of its simple geometry, minimal electrode connections, and simple structure of the superconducting magnet. A heat exchanger, which is installed just downstream of the MHD generator, can regenerate generator exhaust heat in order to minimize waste heat rejection and to improve plant efficiency. Other major components include a staged gas compressor with intercoolers and a radiation cooler.

Table 1 shows typical systems analysis results for an NFR/CCMHD power generation system. It can be seen that the regeneration power is ≈8 MW for an NFR thermal output of 5 MWth, giving a thermal input to the MHD generator of 12.9 MWth. The net electric output of the power plant is 2.76 MWe because the compressor power (1.67 MWe) and pre-ionization power (0.08 MWe) are consumed from the total output power of the MHD generator (4.51 MWe). Input power to the system is 5 MWth, and electric output is 2.76 MWe, which yields a plant efficiency of 55.2 percent. This value is slightly smaller than the previous results using an ICF reactor and can be ascribed to slightly lower gas temperature at the exit of the reactor.

Table 1. Baseline conditions and systems analysis summary.

NFR		
Thermal input power	5	MWth
Reactor output temperature	1,800	K
Reactor output pressure	0.4	MPa
Pressure loss	2.5	%
MHD generator		
Enthalpy extraction ratio	35	%
Isentropic efficiency	80	%
Heat loss	1	%
Compressor		
Isentropic efficiency	85	%
Pressure loss	1	%
Number of stages	1–6	stages
Radiation cooler		
Temperature	300	K
Pressure loss	1	%
Regenerator		
Efficiency	1	
Heat loss	1	%
Pressure loss	1	%
Pre-ionizer		
Efficiency	50	%
Systems analysis summary		
Thermal Input to MHD generator	12.89	MWth
Electric output power	4.51	MWe
Compressor power	1.67	MWe
Pre-ionization power	0.08	MWe
Net output electrical power	2.76	MWe
Total plant efficiency	55.2	%

3. ANALYSIS

For the proposed NFR/CCMHD system, only three issues need to be examined: (1) Number of compressor stages, (2) regenerator efficiency, and (3) radiation cooler temperature. The power balance analysis follows the approach previously outlined by Litchford et al.[7]

3.1 Number of Compressor Stages

Figure 2 shows the compressor power and total plant efficiency compared to the number of compressor stages. Owing to an increased number of intercoolers that can reduce the power needed to compress the working gas, plant efficiency increases with the number of compressor stages. Note, however, that this effect is not significant when it exceeds four compressor stages, and three compression stages are optimum.

3.2 Regenerator Efficiency

Figure 3 shows the temperature-entropy, *T-s*, diagram of the present system for regenerator efficiencies of 1, 0.6, and 0.2. Here, the NFR exit conditions are set as the entropy reference point where both temperature and pressure are fixed. For a regenerator efficiency of 1, the working gas gains thermal energy during processes 1 through 3 (fig. 3) (i.e., heat from the regenerator from process 1 to 2 and heat from the NFR from 2 to 3). Points 3 and 4 correspond to the NFR and MHD generator exits, respectively. Figure 4 shows regenerated power, Q_{reg}, (at 1 to 2 in fig. 3); thermal input to the MHD generator, Q_{MHD}; and total plant efficiency as a function of regenerator efficiency. Here, the temperature difference between high- and low-temperature fluids is assumed as to be 50 K. When regenerator efficiency is decreased (i.e., regenerated heat is reduced), thermal input to the MHD generator is also decreased because the thermal output from the NFR is kept at the same level, 5 MWth. Thus, decreased output power from the MHD generator leads to a decrease in total plant efficiency. If the regenerator is removed from the system, plant efficiency decreases ≈28 percent. If this lower level of plant efficiency is acceptable, the regenerator can be removed from the system in order to reduce specific mass. However, to obtain the same level of electric output as produced by a system with fully regenerated heat, the scale of NFR, MHD generator, and radiation cooler is expected to be doubled. A more detailed comparison should be examined to achieve the lowest specific mass.

3.3 Radiator Cooler Temperature

Figure 5 shows the temperature-entropy, *T-s*, diagram of the present system for radiation cooler temperatures of 300 , 500, and 700 K. The NFR thermal output and MHD enthalpy extraction are the same for all radiation cooler temperatures. However, generated electric power, which corresponds to the area surrounded by the diagram, increases significantly with a decrease in radiation cooler temperature. This means that the plant efficiency is strongly dependent on cooler temperature. Figure 6 shows radiated waste heat, Q_{rad}, which consists of waste heat from the gas cooler, Q_{GC}, and the intercoolers, Q_{IC}, and total plant

efficiency against radiator temperature. In space, this waste heat must be rejected by the radiation cooler. Therefore, the radiation cooler will be larger in general and cause an increase in specific mass. This radiator temperature is the lowest temperature of the cycle and also has a strong influence on plant efficiency. It can be seen in figure 6 that plant efficiency decreases significantly with increasing cooler temperature, and net output power approaches zero when the cooler temperature reaches 800 K. Because the radiated power depends strongly on radiation cooler temperature, lower temperature requires much larger radiation cooler area. Adequate radiation cooler temperature must be clarified.

4. SPECIFIC MASS ANALYSIS

Specific mass, which is mass per unit electrical output power (kg/kWe), must be calculated for each component of the NFR/CCMHD system. This analysis has been carried out on the basis of prior work by Litchford et al.[7]

The resulting system specific mass predictions are shown in figure 7 as functions of net output power and radiator temperature. A radiator temperature of ≈600 K provides the minimum specific mass for all net output power levels. In order to clarify why the minimum specific mass is achieved at the radiation temperature of ≈600 K, mass fractions of major components are shown in figure 8 for radiation cooler temperatures of 400, 600, and 800 K. When radiator temperature increases, radiation area becomes smaller to release waste heat, and as a result the specific mass of the radiator is also reduced, as shown in figure 8. At the same time, however, a larger MHD generator and a larger superconducting magnet are required to provide the same net electrical output power because total plant efficiency declines with increasing cooler temperature. As shown in figure 8, the mass fraction of the MHD generator and magnet at a radiation temperature of 800 K is 36.4 percent, which is twice as large as the mass fraction when at a radiation temperature of 600 K. On the other hand, the mass of the radiator itself is large and accounts for >50 percent of the total system mass at a radiator temperature of 300 K. This results in an increase of specific mass compared with the 600 K case.

If an appropriate radiator temperature (≈600 K) is chosen, the specific mass decreases with increasing net electric output power, as can be seen in figure 7. The expected result is a system specific mass of ≈3 kg/kWe at 1 MWe, 2–3 kg/kWe at 2 MWe, and <2 kg/kWe for >3 MWe. These values are in general agreement with the results reported in reference 8. The present NFR/CCMHD power generation system could provide both a higher plant efficiency and a much lower specific mass for multimegawatt electrical power levels in comparison with other energy conversion systems.

5. RESEARCH AND TECHNOLOGY PLAN

It has been confirmed that the proposed NFR/CCMHD power generation system has the potential to achieve a specific mass of less than 3 Kg/kWe for multimegawatt space power plants. Therefore, we propose a three-phase research and development plan of CCMHD generator, as follows: (1) Phase I—proof of principle, (2) Phase II—demonstration of power generation, and (3) Phase III—prototypical closed loop test.

5.1 Phase I—Proof of Principle

The performance of a CCMHD generator using an He/Xe mixture as working medium depends on ionization and recombination processes.[11] Furthermore, stable operation in the regime of a fully ionized seed and avoidance of ionization instability can not be expected because the ionization potential of Xe is close to that of He. Previous studies have shown that He/Xe plasma can be kept stable, and performance comparable to alkali-metal seeded systems can be expected when the characteristic time of recombination is long compared to the plasma residence time. In this phase, therefore, the main objective is to determine whether or not the ionization level (i.e., electron number density and electrical conductivity) can be kept high throughout the disk MHD channel. In practice, the ionization level is electrically elevated well above the thermal equilibrium level using a pre-ionizer at the disk inlet. If the characteristic time for recombination is much longer than the residence time of the working gas in the channel, the process can be considered "frozen," and the ionization level can be kept high. In this case, the plasma becomes stable and high generator performance can be achieved without the presence of alkali-metal seed. To understand this process, it is necessary to measure electron number density and electrical conductivity in the decay region downstream of the pre-ionization source.

Figure 9 shows a schematic of the proof-of-principle experiment. The mass flow rate of the mixture in the apparatus is 0.16 kg/s, which is the same as for the power demonstration in Phase II. The gas mixture will be ionized in the plenum using a radio frequency discharge, microwave, helicon, or electron beam pre-ionization system. In order to achieve an ionization degree of 10^{-4}–10^{-6}, pre-ionization power is estimated to be ≈3 kWe, assuming an ionization efficiency of 50 percent. An acceleration nozzle is located between the pre-ionization chamber and the test section to simulate the MHD channel entrance region. Changes in electron number density and electrical conductivity along the flow direction will be measured in the test section using microwave cut-off, attenuation, and phase shift. The time duration of the experiments will be seconds to minutes, depending on measurement requirements. Operating conditions are summarized in table 2.

Table 2. Phase I experiment operating/test conditions.

Location	M	T (K)	p (MPa)	u (m/s)	A (cm^2)
Pre-ionizer	0.3	291	0.186	301	17.3
Test section	1	225	0.097	883	8.7

Plenum Stagnation Conditions: T_0=300 K, P_0=0.2 MPa.

5.2 Phase II—Power Generation Demonstration

Phase II efforts will be devoted to power generation demonstration experiments. A schematic of the Phase II experiment is shown in figure 10, where scale and operating parameter ranges are governed by both cost and research and development requirements. A He/Xe working gas mixture is first heated to 1,800 K, the expected exit temperature of an NFR, using an electric heater and a 1.5 MWe Aerotherm arc heater. The gas exit temperature of the vapor core reactor is considered to be in that range while the exit temperature of direct-drive gas-cooled reactor would be around 900 to 1,150 K.[8,9] Next, pre-ionized working gas is introduced to the disk MHD generator, and a magnetic field is applied by a 3-T superconducting magnet. Because a higher Hall parameter must be maintained in the disk generator channel, the stagnation pressure should be ≈0.2 MPa at this magnetic field strength with a Mach number of around 2 to 2.5 at the disk channel inlet. For the pin-type gas-cooled reactor, the operating pressure is ≈2.4 MPa. Thus, the optimum design of an MHD generator and operating conditions for lower temperature and higher gas pressure should also be studied. In the Phase II configuration, the exit of the generator must be connected to the ejector to keep the back pressure suitably low.

To obtain the specified thermal input, the He/Xe mixture would be preheated to 1,050 K using an electric heater then additionally heated to 1,800 K using an arc heater having a net input power to the working gas of 750 kW; therefore, the total thermal input to the working gas is 1.5 MWth. This thermal input is comparable to the He shock tube experiments at T.I.T., which has demonstrated enthalpy extraction ratios >30 percent. Stagnation gas temperature must be close to the exit temperature of an NFR, which was set at 1,800 K. The required net electric power for pre-ionization of Xe, up to an ionization degree of 10^{-4} to 10^{-6}, is ≈4.7 kWe, and pre-ionizer power must be ≈10 kWe if ionization efficiency is assumed to be ≈50 percent. The proposed operating conditions and results of the preliminary MHD generator design are summarized in table 3. The MHD channel-shape design is shown in figure 11. Inlet and exit radii are 0.05 and 0.2 m, respectively. Channel height is <0.02 m and total channel height, including thermal insulator and support structure, is expected to be <0.1 m. This channel fits within Marshall Space Flight Center's (MSFC's) existing 3-T superconducting magnet, and operation with a higher magnetic field, if available, could reduce the warm gap from 12 to 5 in. Figure 12 shows plasma parameter distributions in the disk MHD channel.

In the Phase II power generation experiment, it should be possible to demonstrate >20 percent enthalpy extraction. In the system analysis, an enthalpy extraction of 35 percent and isentropic efficiency of 80 percent are assumed. This level of performance can be confirmed through numerical simulations if the magnetic field strength is increased to 8 T.

5.3 Phase III—Prototypical Closed Loop Test

Phase III efforts will be devoted to constructing a complete closed loop with a simulated nuclear heat source and conducting continuous power generation tests to confirm generator performance. The main objectives will be to confirm closed-loop system stability, start-up and shut-down operations, output controllability, system reliability, and durability. Ultimately, the CCMHD system should be connected to an NFR as a ground test demonstration.

Table 3. Baseline conditions and MHD disk generator design summary

Baseline operating conditions		
Working fluid	He/Xe (seed)	
Thermal input power	1.5	MWth
Stagnation temperature	1,800	K
Stagnation pressure	0.2	MPa
Mass flow rate	0.16	kg/s
Seed fraction	10^{-5}–10^{-4}	
Pre-ionization power	4.7	kWe (net)
MHD disk generator design summary		
Inlet radius	5	cm
Exit radius	20	cm
Inlet height	1.5	cm
Exit height	1.1	cm
Inlet Mach number	2	
Exit Mach number	0.64	
Inlet radial velocity	2,310	m/s
Exit radial velocity	1,340	m/s
Output current	122.4	A
Output voltage	2,905	V
Output electrical power	0.356	MWe
Enthalpy extraction ratio	23.7	%

6. CONCLUSIONS

A multimegawatt class NFR powered CCMHD space power plant cycle using a He/Xe working gas has been studied. This included a detailed system analysis and the formation of a comprehensive research and technology plan.

The major conclusions of the system analysis are as follows:

- A CCMHD nuclear space power generation system, which does not rely on the use of condensable alkali-metal seed, was proposed. The total plant efficiency was expected to be 55.2 percent, including pre-ionization power.

- Three compressor stages were sufficient from a plant efficiency perspective.

- Regenerator efficiency affected the total plant efficiency; if removed, plant efficiency declined from 55 to 28 percent for the full regenerating case.

- Total plant efficiency depended significantly on radiation cooler temperature. The radiator temperature also had a strong influence on power plant specific mass.

- Minimum system specific mass occurred at a radiation cooler temperature of ≈600 K.

- System specific mass was estimated to be ≈3 kg/kWe for a net electrical output power of 1 MWe, 2–3 kg/kWe at 2 MWe, and ≈2 kg/kWe at >3 MWe.

A three-phase research and technology development plan was proposed to include the following activities:

- Phase I—Proof of Principle. Confirm ionization and recombination processes in an He/Xe plasma using a simple cold gas flow experimental facility.

- Phase II—Power Generation Demonstration. Preheat the working mixture with ≈1.5-MWth input to generate a 1,800 K working temperature at the inlet of a subscale MHD generator. An existing 3-T split-coil superconducting magnet would be used to minimize research costs. Based on these assumptions, numerical simulation showed that it would be possible to achieve an enthalpy extraction in excess of 20 percent.

- Phase III—Prototypical Closed Loop Test. Conduct system tests with a simulated heat source rather than an actual NFR. Confirm closed loop system stability, start-up and shut-down operations, output controllability, system reliability, and durability.

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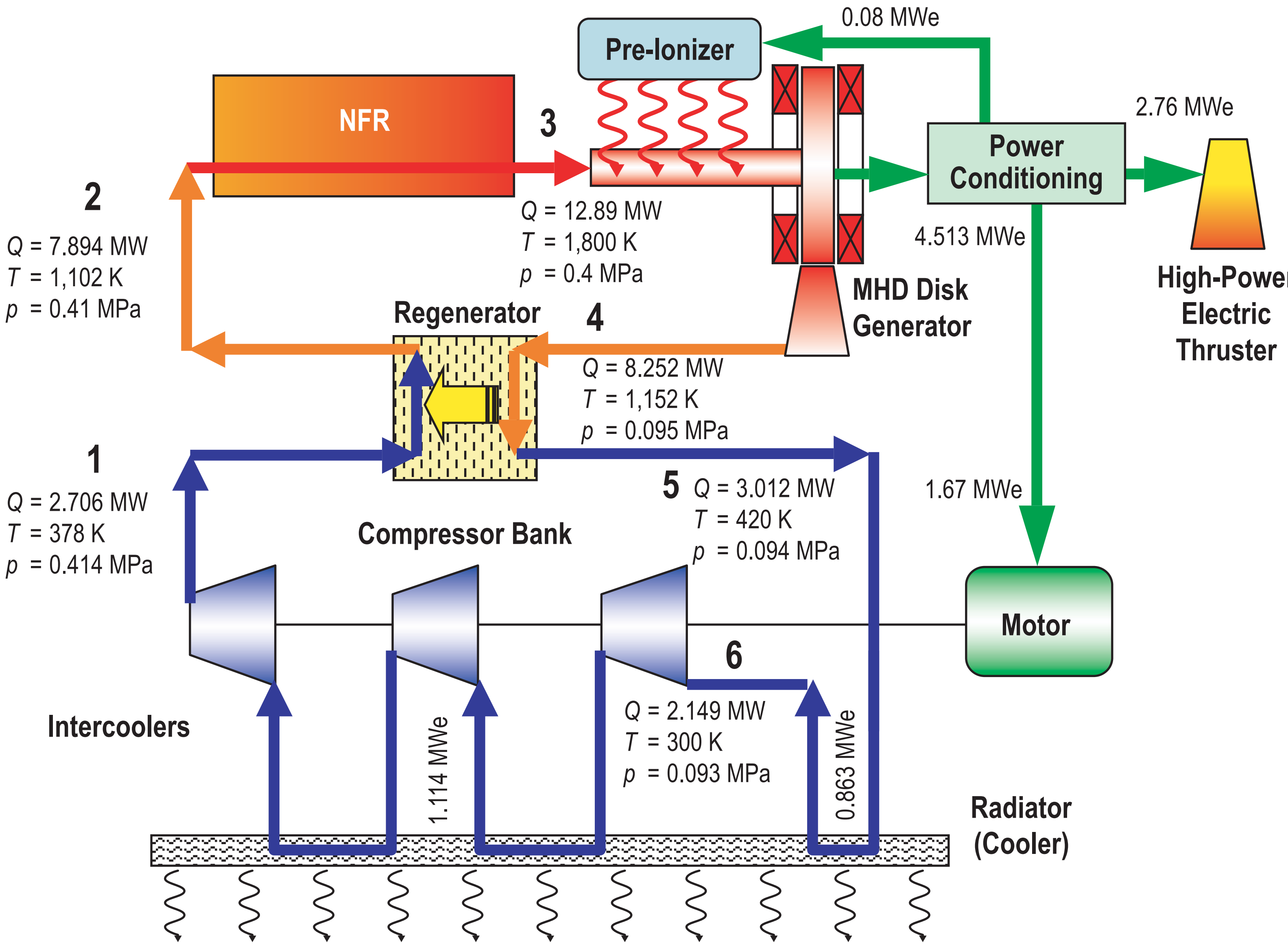

Figure 1. Schematic of NFR/CCMHD space power generation system.

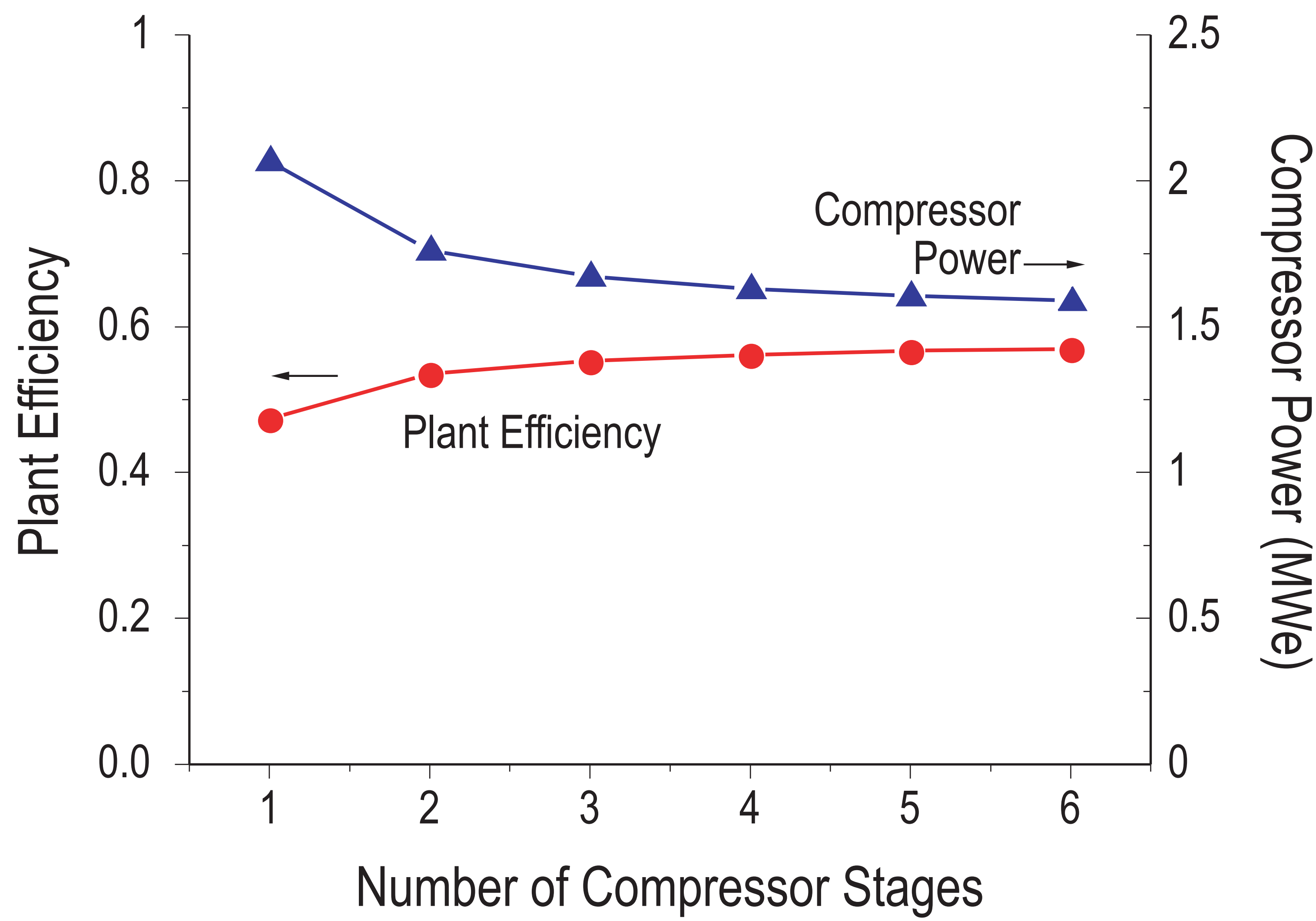

Figure 2. Influence of compressor stage number on compressor power and plant efficiency.

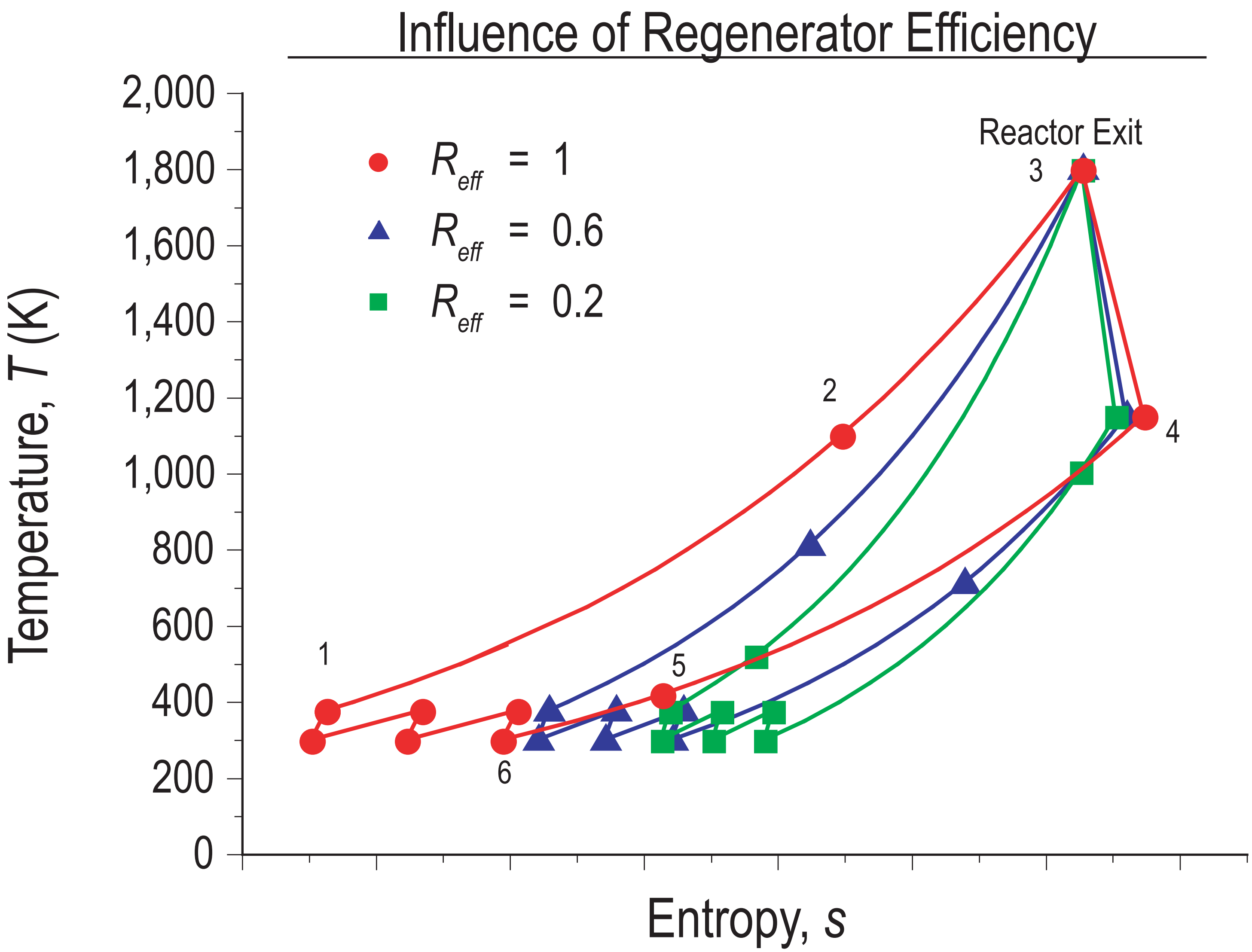

Figure 3. T-s diagram for NFR/CCMHD system assuming regenerator efficiencies 1, 0.6, and 0.2.

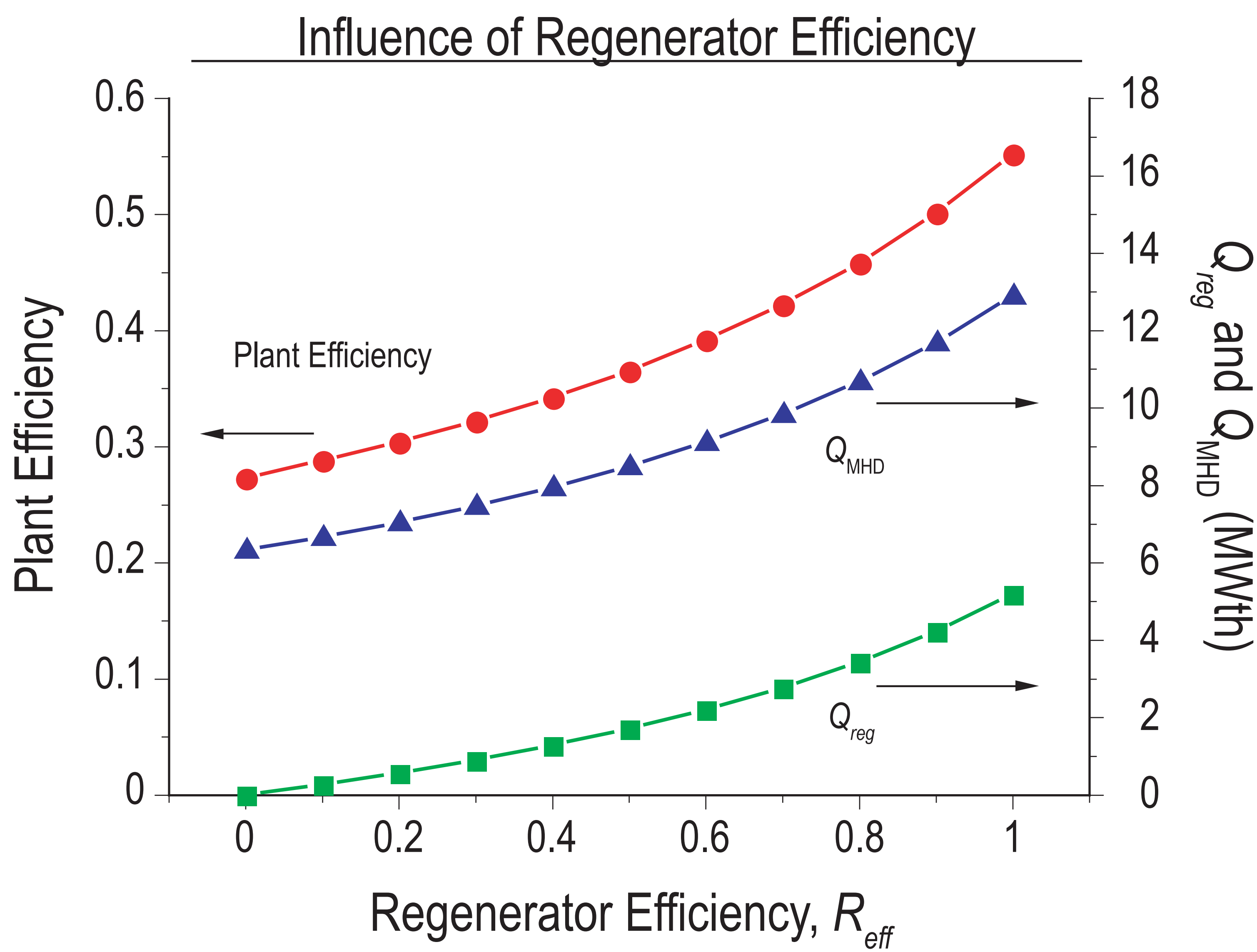

Figure 4. Influence of regenerator efficiency on regenerated power, MHD thermal power, and plant efficiency.

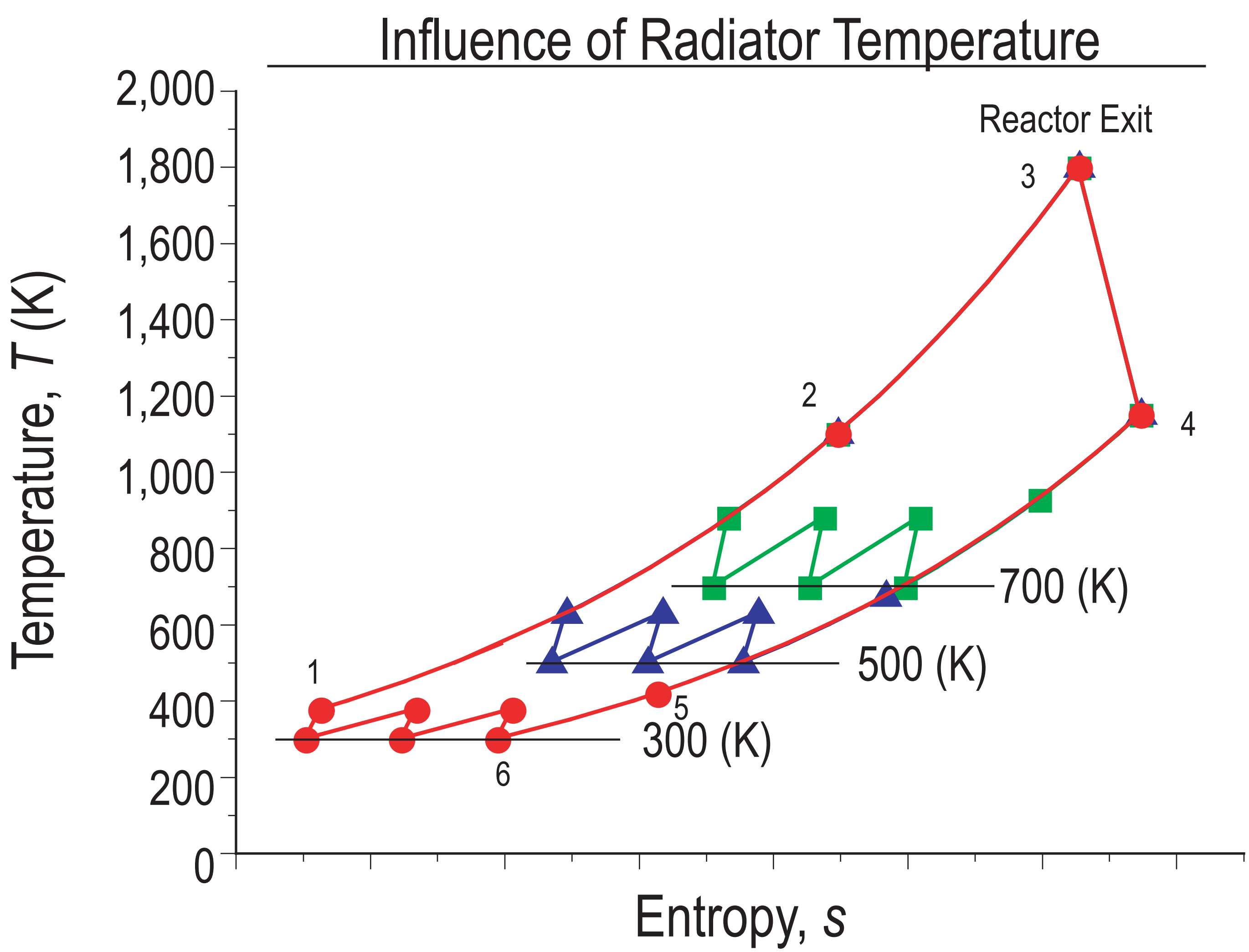

Figure 5. *T-s* diagram of the present NFR/CCMHD system for radiation cooler temperatures 300, 500, and 700 K.

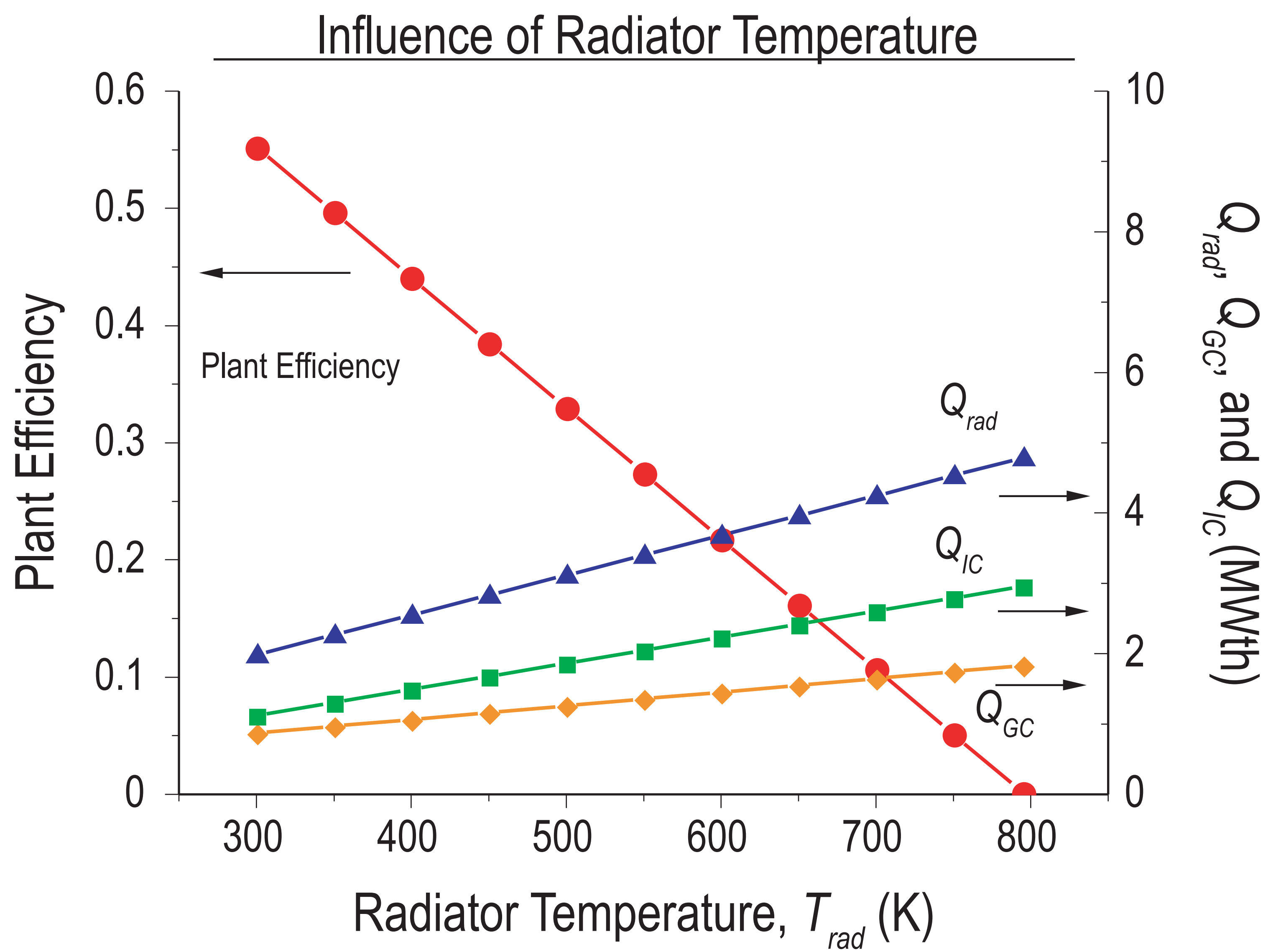

Figure 6. Influence of radiation cooler temperature on radiated heat power and plant efficiency.

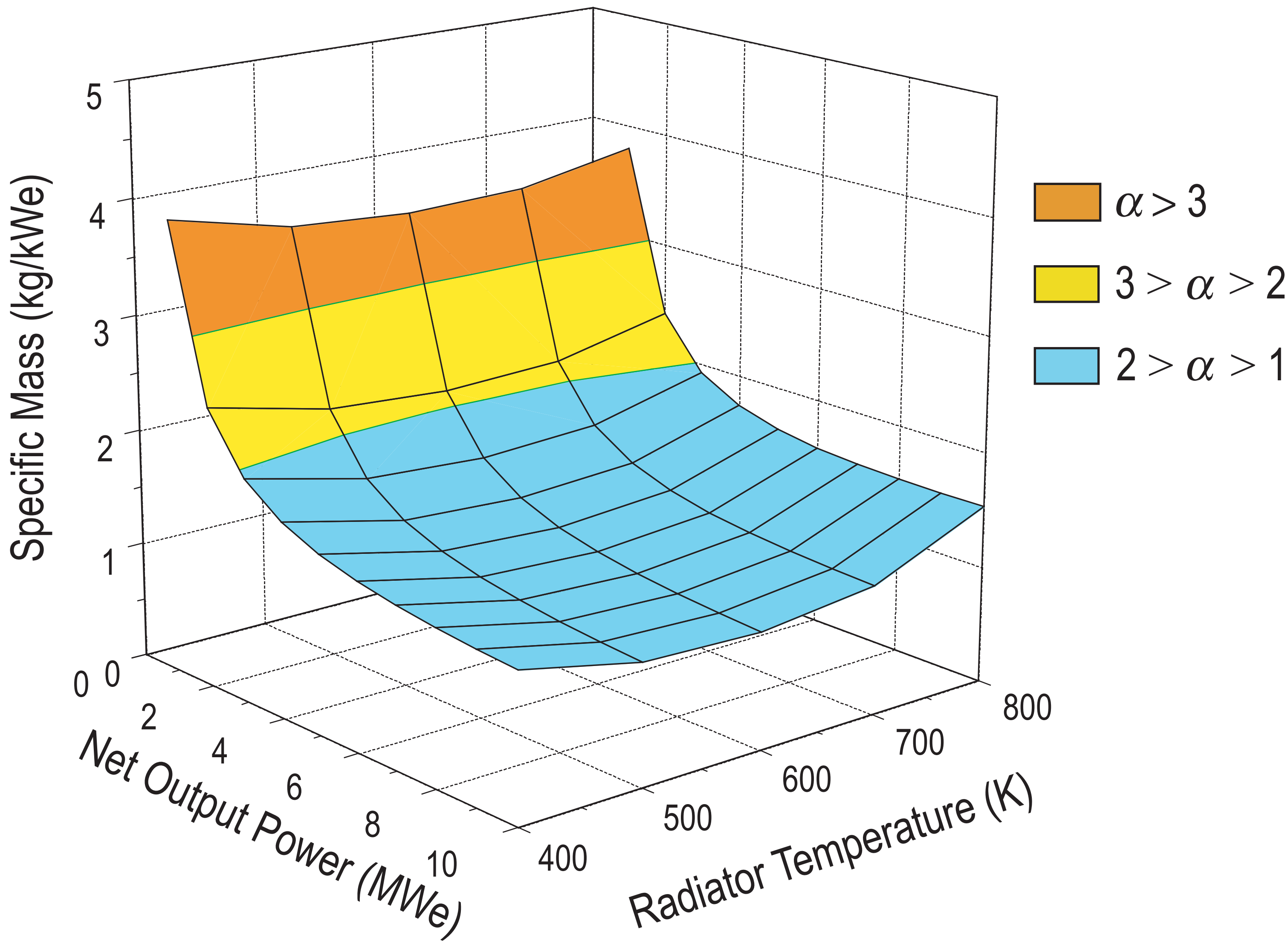

Figure 7. Calculated system specific mass as functions of net output power and radiator temperature.

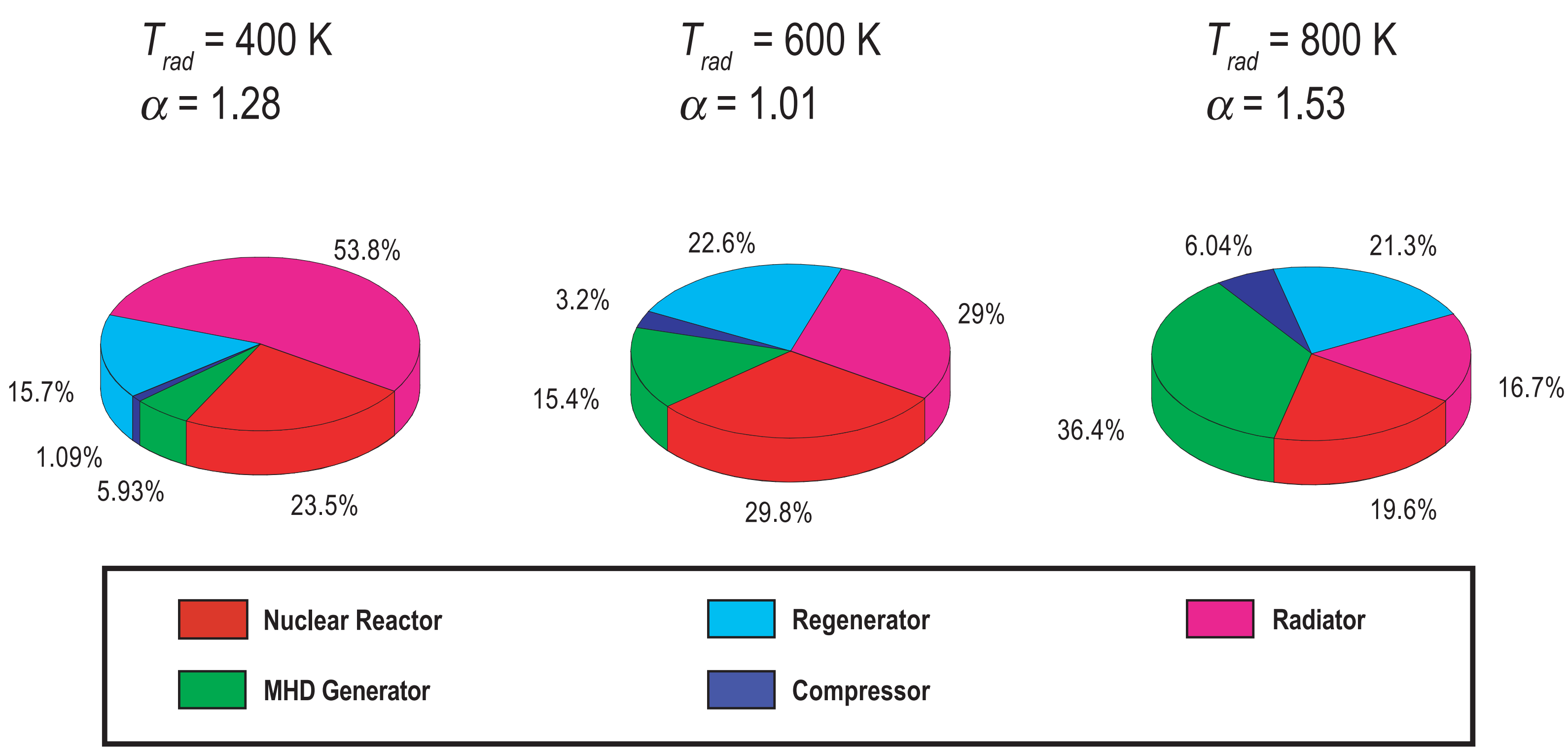

Figure 8. Mass fraction of major components of the NFR/CCMHD system for radiator temperatures 400, 600, and 800 K.

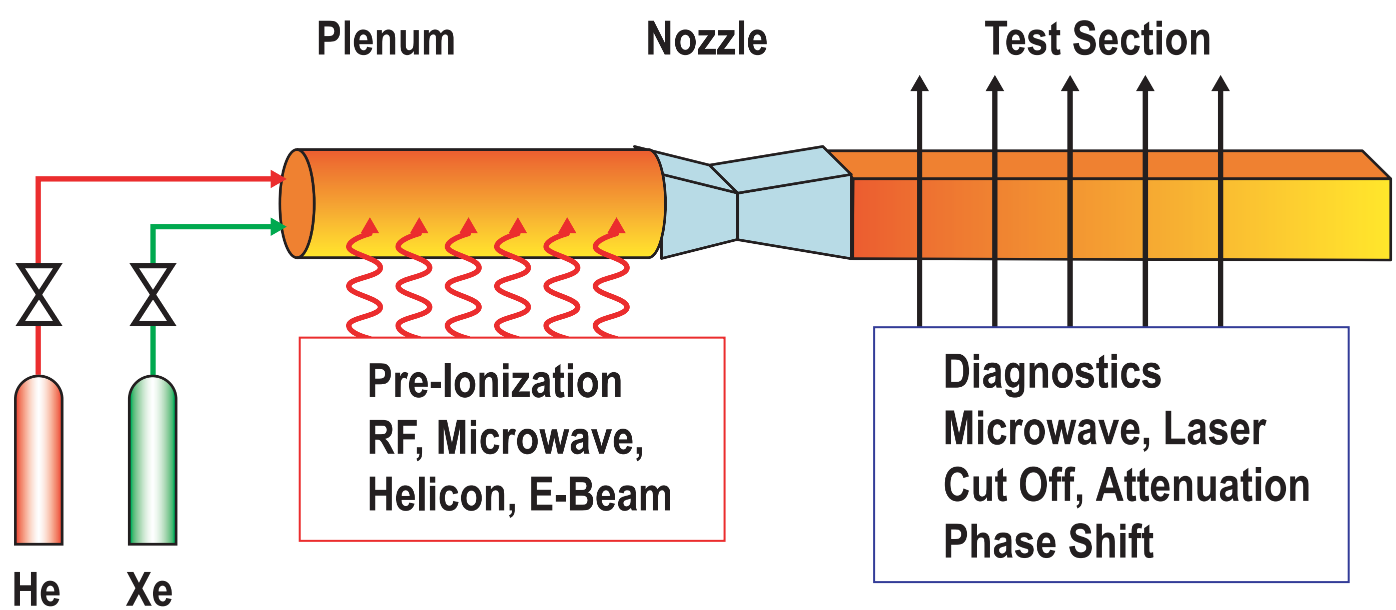

Figure 9. Conceptual design of phase I, proof-of-principle experiment.

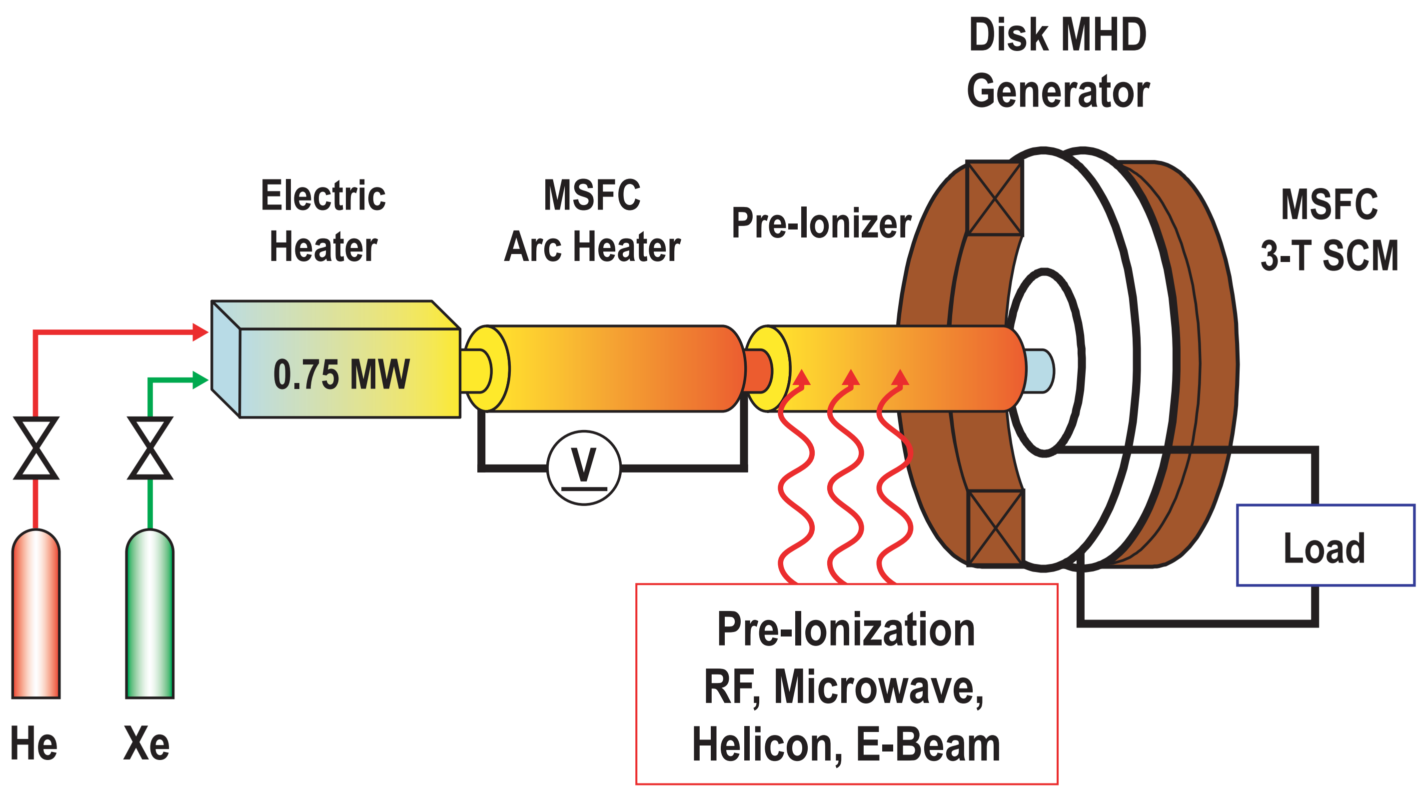

Figure 10. Conceptual design of phase II, MHD power generation demonstration experiment.

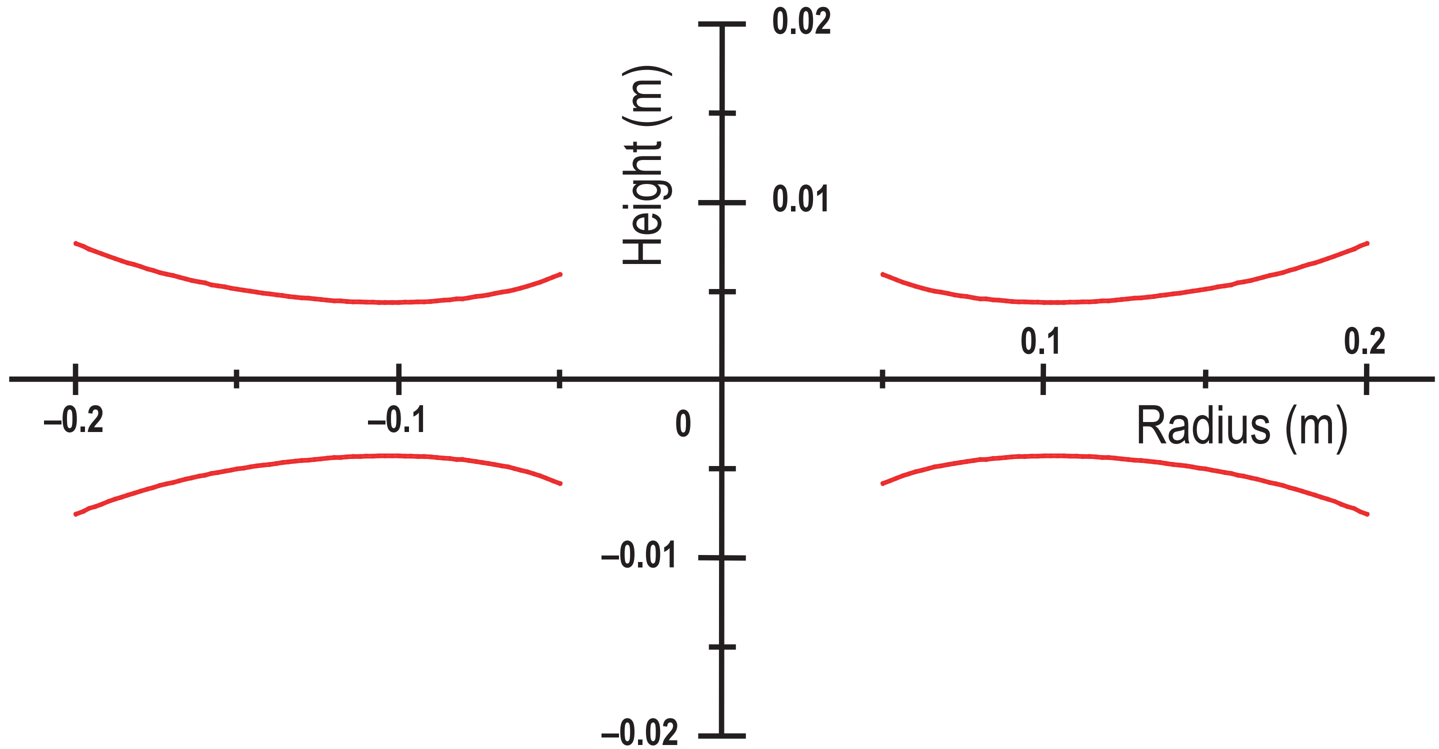

Figure 11. Design lofting of phase II disk generator channel.

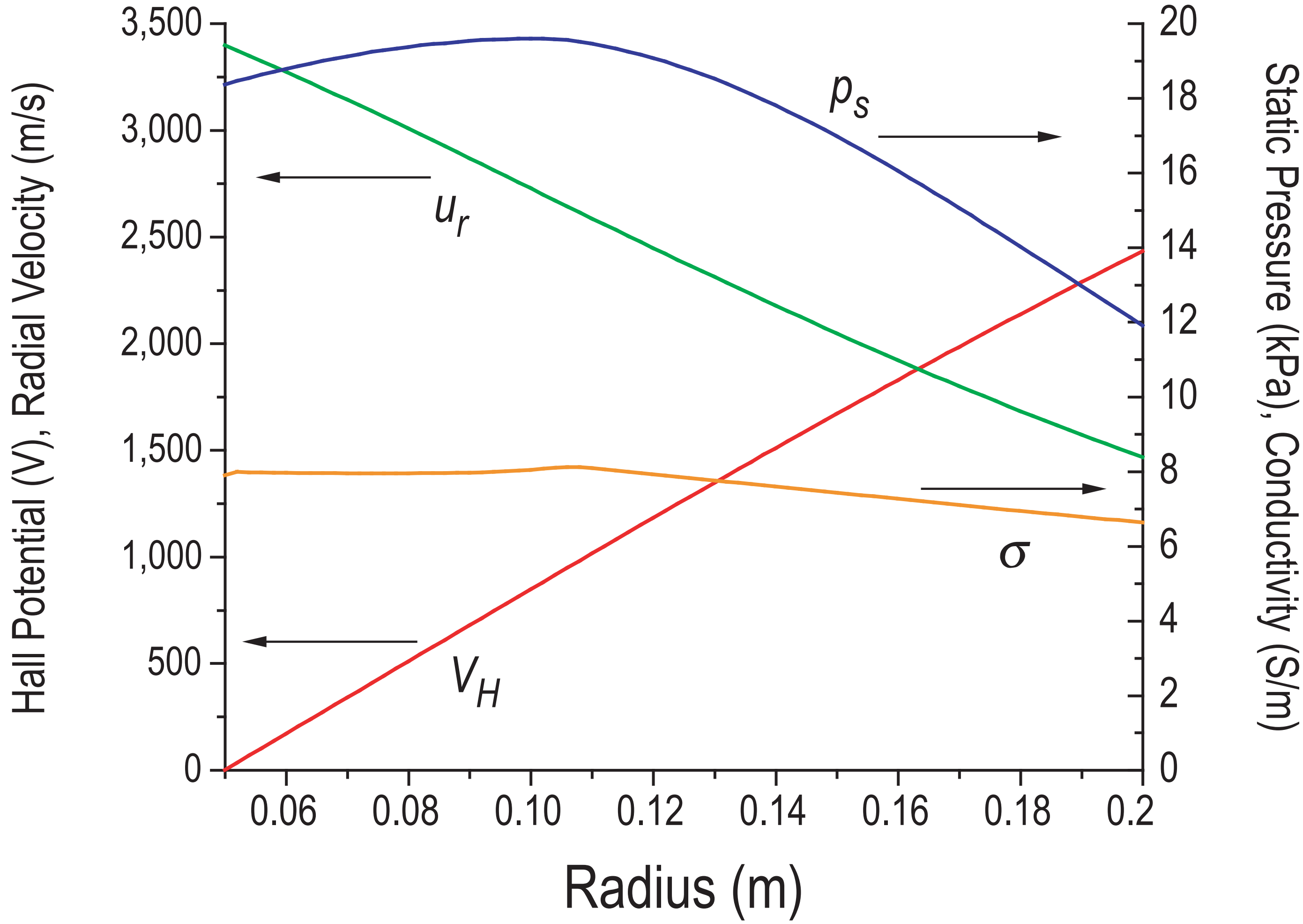

Figure 12. Computed plasma parameter variations in phase II disk generator channel.

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R.J. Litchford and N. Harada*

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13. ABSTRACT *(Maximum 200 words)*
A multimegawatt-class nuclear fission powered closed cycle magnetohydrodynamic space power plant using a helium/xenon working gas has been studied, to include a comprehensive system analysis. Total plant efficiency was expected to be 55.2 percent including pre-ionization power. The effects of compressor stage number, regenerator efficiency, and radiation cooler temperature on plant efficiency were investigated. The specific mass of the power generation plant was also examined. System specific mass was estimated to be 3 kg/kWe for a net electrical output power of 1 MWe, 2–3 kg/kWe at 2 MWe, and ≈2 kg/KWe at >3 MWe. Three phases of research and development plan were proposed: (1) Phase I—proof of principle, (2) Phase II—demonstration of power generation, and (3) Phase III—prototypical closed loop test.

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